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THESIS

MODELS FOR CONDUCTING ECONOMIC ANALYSIS
OF ALTERNATIVE FUEL VEHICLES

by

Danny R. Grenier

June 1987

Thesis Advisor: Dan C. Boger

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Models for Conducting Economic Analysis of Alternative Fuel Vehicles

by

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Submitted in partial fulfillment of the
requirements for the degree of

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June 1987

ABSTRACT

The present status of alternative fuel vehicles, specifically electric-powered and compressed natural gas-powered vehicles is summarized. Specific advantages and disadvantages of each vehicle type, in comparison to the gasoline-powered vehicle, are reviewed. A life cycle cost model is formulated for each vehicle type. An integer linear program is derived and explained as a means of determining the optimal mix of vehicles for a command's transportation fleet. The models are tested by running several test cases using data from the Naval Postgraduate School transportation office.

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I. INTRODUCTION

Today's military managers must contend with decreasing budgets while mission requirements continue to expand. In order to meet these expanding requirements, military managers must conserve the scarce financial resources available to them.

The Public Works Center Transportation Office is required to provide vehicles for the transportation requirements of the commands it supports. These transportation requirements run the gamut from maintenance vehicles to passenger sedans to passenger buses. The means of propulsion for all of these vehicles is usually the internal combustion engine with gasoline as the fuel source.

Recent history has shown the price of gasoline to be somewhat less than stable. This instability can be a financial manager's nightmare. Departmental budgets are forecasts or predictions of what funds the department believes it will require for some future period. In the government, this future period can be more than a year away. Thus, the budget the transportation manager submits today can be drastically affected by an increase in the price of gasoline tomorrow. What the transportation officer desires is a fuel source which is cost effective and stable in price.

Two alternative fuel source vehicles that have generated interest within the transportation industry are electric-powered vehicles and compressed natural gas-powered vehicles.

This thesis looks at these two alternative fuel vehicles and compares them to the present baseline of the gasoline-powered internal combustion engine vehicles. In order to simplify matters, this thesis will only deal with sedans, vans, and light trucks.

Formulas for computing the life cycle costs of the vehicles are derived in the thesis. After determining the life cycle costs of the various types of vehicles, the transportation manager must decide what mix of the various types of vehicles would allow him to meet his operational requirements at the lowest cost. In other words, what mix allows him to optimize his transportation budget?

The thesis explains the use of a fixed charge linear program to obtain the optimal mix of vehicles. Linear programming is an operations research tool which is used to determine the optimal allocation of limited resources, in this case, the transportation budget. In doing linear programming, the manager can subject the results to sensitivity analysis which allows the manager to test the optimal solution by changing the various constraints such as the funding level or various cost elements (i.e., fuel cost,

maintenance cost, operating cost) and observing the effects on the optimal solution.

A. PROBLEM STATEMENT

The instability of the cost of gasoline has stimulated an interest in alternative fuel vehicles. A means to compute the life cycle costs of the various types of vehicles is required. Having determined the life cycle costs of the various vehicle types, the transportation manager requires a means of determining the optimal mix of the vehicle types based on his budget constraint and mission requirements.

B. OBJECTIVE

The research objective is to derive a procedure for computing the various vehicle life cycle costs, then use these life cycle costs to determine the optimal mix of vehicle types. The underlying objectives are:

1. Present an overview of the present state of the art of the electric-powered vehicle industry and the compressed natural gas-powered vehicle industry. This overview will include an assessment of the operational capabilities of both the electric-powered vehicle and the compressed natural gas-powered vehicle.

2. Develop a model for determining the life cycle costs of the various vehicle types.

3. Develop a fixed charge linear program for determining the optimal mix for a typical Public Works Center transportation fleet.

C. ALTERNATIVES

The alternatives to the gasoline-powered internal combustion engine vehicle that are considered are the electric-powered vehicle and the compressed natural gas-powered vehicle.

The electric-powered vehicle has been tested extensively by large companies and the United States Postal Service. While it is not a widely used vehicle in the United States, it is quite popular overseas. There are various limitations on the use of the electric vehicle due to its limited range and cruising speed.

The electric vehicle must be recharged daily. A few models of electric vehicles are equipped with an onboard charging unit but this is the exception rather than the rule. As such, the electric vehicle is usually required to return to the charging unit each night. This makes the electric vehicle impractical for extended trips.

Another limitation on the use of the electric vehicle is the cruising speed attainable by the vehicle. While some vehicles are able to attain speeds of over 55 miles per hour, this, again, is the exception rather than the rule. A drawback of attaining high speeds in an electric vehicle is that the range of the vehicle is drastically decreased with an increase in speed. Most electric vehicles are designed to operate most efficiently at speeds of up to 35 miles per hour.

The compressed natural gas-powered vehicle has been used extensively by natural gas utility companies in the United States. Much like the electric vehicle, it enjoys more popularity overseas than in the United States. The compressed natural gas-powered vehicle that is most popular is actually a conversion of the gasoline-powered internal combustion engine vehicle. The conversion process allows the vehicle to operate using either compressed natural gas or gasoline. Due to this ability to use two fuels, it is termed a dual fuel vehicle.

Due to this dual fuel capability, the compressed natural gas vehicle does not have the range limitations that the electric vehicle carries. If a compressed natural gas vehicle is required to operate in an area where natural gas refueling equipment is not available, a simple turn of a valve will switch the vehicle from natural gas fuel to gasoline.

The primary limitation caused by the compressed natural gas conversion of the gasoline internal combustion engine vehicle is a loss of cargo space due to installation of the compressed natural gas cylinders.

The electric-powered vehicles and the compressed natural gas-powered vehicles will be judged against the baseline of the gasoline-powered internal combustion engine vehicle. Due to the widespread use of the gasoline vehicle and its operational capabilities, there are few limitations on the

vehicle type. Range is unlimited due to the many gasoline stations in the United States and overseas. Nearly all gasoline-powered vehicles can easily attain the national speed limit of 55 miles per hour.

Due to the unlimited range and the high cruising speed attainable by gasoline-powered vehicles, these vehicles are considered high performance vehicles. In contrast, low performance vehicles would be characterized by cruising speeds of less than 55 miles per hour and reduced range.

For the purpose of this thesis, the optimal vehicle is the vehicle which meets the minimum mission requirements placed upon it at the lowest life cycle cost.

D. ALTERNATIVE SELECTION CRITERIA

The two keys to determining the optimal vehicle for a particular task are:

1. Determining the requirements that will be placed upon the vehicle.
2. Determining which vehicle type can meet the minimum requirements of the task at the lowest life cycle cost.

These two keys require the Public Works Center transportation officer to first determine the types of requirements that are placed on his vehicle fleet. These requirements are usually in terms of range, cruising speed, and load.

Once the transportation officer has determined how many high performance vehicles and low performance vehicles are

required to meet the requirements placed on his department, he can then look at meeting these requirements with the lowest life cycle cost vehicle type.

E. MEASURES OF EFFECTIVENESS

The following measures of effectiveness are used to determine whether a vehicle type is classified as high performance or low performance.

1. Range--Range is defined as the distance a vehicle can travel between refuelings. For the purposes of this thesis, the terms refueling and recharging are synonymous. A high performance vehicle is capable of unlimited range. A low performance vehicle's range is limited by the location of its refueling station (homebase).

2. Maximum cruising speed--The maximum cruising speed is defined as the maximum speed a vehicle must be able to attain and travel at for an extended period of time. This is not to be confused with the maximum speed attainable by a vehicle which is the highest speed a vehicle can attain but can't hold for an extended period of time without risking damage to the vehicle. A high performance vehicle is capable of attaining a maximum cruising speed of 55 miles per hour, the national speed limit. A low performance vehicle's maximum cruising speed is less than 55 miles per hour.

The load capabilities of the vehicle types are more a function of the individual vehicle design rather than the vehicle type and as such load capability will not be used as a measure of effectiveness.

F. ASSUMPTIONS

In order to conduct this study, certain assumptions have been made. Those assumptions are:

1. The number of vehicles needed to meet the requirements placed upon the Public Works Center transportation

office will not change due to the type of vehicle chosen to meet the requirement. The number of vehicles in the transportation office fleet will remain constant.

2. Future requirements placed upon the vehicles will be consistent with past requirements. Required range and maximum cruising speed for a particular vehicle will not change in the near future.

3. Initial procurement cost, maintenance cost per mile, operating cost per mile, and fuel efficiency ratings are equal for each vehicle in a particular vehicle type (i.e., gasoline-powered, electric-powered, or natural gas-powered).

4. All vehicles will be procured at the same time, Year 1, and disposed of at the end of their useful life.

5. All cost data used in the life cycle cost model will be in 1986 dollars. Cost figures from research material will be adjusted to reflect value in 1986 dollars. Adjustments will be made in accordance with Table 1, which lists the Consumer Price Indices for gasoline, natural gas, electricity, new automobiles, and the general price index of all items.

G. RESEARCH METHODS

A literature search was conducted to obtain a bibliography of articles, studies, and research papers written on the current state of the art of electric-powered vehicles and compressed natural gas-powered vehicles. The search included articles on the claimed performance capabilities of the alternative fuel vehicles as well as actual use studies done on the vehicles. These performance capabilities were used to classify the alternative fuel vehicle types as either high or low performance vehicles.

TABLE 1

CONSUMER PRICE INDICES FOR
1970 THROUGH 1986

1967 = 100

Year	Gasoline	Natural Gas	Electricity	New Autos	All Items
1970	105.6	108.5	106.2	107.6	116.3
1971	106.3	116.2	113.2	112.0	121.3
1972	107.6	122.3	118.9	111.0	125.3
1973	118.1	127.9	124.9	111.1	133.1
1974	159.9	143.9	147.5	117.5	147.7
1975	170.8	172.5	167.0	127.6	161.2
1976	177.9	201.2	177.6	135.7	170.5
1977	188.2	239.3	189.3	142.9	181.5
1978	196.3	263.1	203.4	153.8	195.4
1979	265.6	305.3	219.1	166.0	217.4
1980	369.1	363.9	253.4	179.3	246.8
1981	410.9	414.9	291.5	190.2	272.4
1982	389.3	497.2	320.3	197.5	289.1
1983	376.3	580.1	330.6	202.6	298.4
1984	370.2	584.4	351.8	208.5	311.1
1985	378.9	556.1	357.5	219.2	323.4
1986	262.5	523.8	352.1	231.7	325.7

Note: Indices cited for 1985 and 1986 are the indices as of the end of December 1985 and December 1986.

Sources: U.S. Department of Commerce, Statistical Abstract of the United States, 1976 and 1986.

U.S. Department of Labor, CPI Detailed Report, December 1985 and 1986.

The literature provided cost data on initial procurement costs, maintenance costs, operating costs, and supporting equipment costs of the alternative fuel vehicles.

The literature search provided points of contact for additional information. Telephone interviews were conducted with several electric vehicle manufacturers and the American Gas Association. As a result of these telephone interviews, additional research material was forwarded to the thesis writer. This additional information included cost and performance data.

The cost data derived from the above research was used to compute a life cycle cost for each alternative fuel vehicle type. The fuel cost rates used in the life cycle cost determination were those rates paid by the Naval Postgraduate School in 1986.

The life cycle cost of the gasoline-powered vehicle was derived using 1986 cost data from the Naval Postgraduate School transportation office. Initial procurement cost, operating cost per mile, and maintenance cost per mile are the computed averages for all gasoline-powered sedans, vans, and light trucks in the Naval Postgraduate School vehicle fleet.

If the study were to determine that an alternative fuel vehicle should be used in the transportation vehicle fleet, there would be a fixed cost of the price of the fueling station. In the case of an electric-powered vehicle, the

fueling station would be a charging unit. For a compressed natural gas-powered vehicle, the refueling station would be a natural gas compressor. Due to this fixed charge component in the life cycle cost, a fixed charge linear program was deemed appropriate for determining the optimal mix of vehicle types in the vehicle fleet. Constraints in the linear program were derived from the transportation office budget and the operational requirements placed upon the vehicle fleet.

H. SUMMARY

This thesis reviews the current state of the art in electric-powered vehicles and compressed natural gas-powered vehicles. A means of determining the mix of high and low performance vehicles required to meet mission requirements is submitted. A model for computing the life cycle cost of a vehicle type is explained and then used in a fixed charge linear program to determine the optimal mix of vehicles to meet the requirements placed upon the vehicle fleet.

The models and linear program are tested by using the Naval Postgraduate School transportation office vehicle fleet as a test case.

Chapter II of the thesis evaluates the advantages and disadvantages of each of the vehicle types. Based on the range and maximum cruising speeds of the vehicle types, the vehicles are classified as either high or low performance vehicles.

In Chapter III, the cost components of the life cycle cost model are explained and the life cycle cost model is formulated. The costs associated with each vehicle type are then put into the life cycle cost model to obtain the life cycle costs for each vehicle type.

In Chapter IV, the fixed charge linear program model is explained. The life cycle costs computed in Chapter III are then put into the fixed charge linear program. The constraints used in the fixed charge linear program are based on the Naval Postgraduate School transportation office's mission requirements and budget. By using the fixed charge linear program, an optimal mix of vehicles for the Naval Postgraduate School vehicle fleet is determined.

II. ALTERNATIVES

This chapter begins with a brief description of the electric-powered vehicle and how it operates. Performance data derived from tests of various models of electric-powered vehicles will be presented for use in classifying the electric-powered vehicle as either high or low performance. Cost data concerning the electric vehicle's procurement cost, maintenance cost, and fuel cost will also be presented.

Following the section on electric-powered vehicles, the compressed natural gas-powered vehicle will be described. Performance data will be presented as will cost data on procurement, maintenance, and fuel.

A. ELECTRIC-POWERED VEHICLES

1. Background

At the beginning of the twentieth century, the electric vehicle was in direct competition with the gasoline powered vehicle. The scarcity of gasoline stations made the electric vehicle a viable option to the gasoline vehicle. However, with the rapid growth of the gasoline service station industry came the demise of the electric-powered vehicle. The demise of the electric-powered vehicle was attributable to its limited range and unreliable power source, the batteries. [Ref. 1:p. 24]

During World War II, due to gas shortages and rationing of gasoline, there were approximately 6,000 electric-powered vehicles in operation in the United States. Following the war, the growth of the electric vehicle industry continued until it reached its highpoint in the 1960s when there were approximately 45,000 electric vehicles in use in the United States. At that time, the electric vehicle was mainly being used for delivery service in industries such as the dairy industry. [Ref. 1:p. 24]

An electric-powered vehicle with a range of 40 to 50 miles between chargings could be built with the technology available today. An electric vehicle with this range would be capable of meeting 95% of the daily driving needs of a typical United States car owner. [Ref. 2:p. 1388]

The electric vehicle manufacturing industry in the United States consists mainly of small manufacturing firms. Most of the United States electric vehicle manufacturers believe that the most popular and efficient electric-powered vehicle model is either the small passenger car or the small van. The body design of the vehicle is most often a conversion of an existing gasoline vehicle's body. [Ref. 3:pp. 629-630]

Since the recent oil glut began in the early 1980s, many of the small electric-powered vehicle manufacturers have gone out of the electric vehicle production business citing low demand for electric vehicles. However, the

electric vehicle industry continues to grow overseas, especially in Great Britain.

The largest single test program of electric-powered vehicles was conducted by the United States Postal Service. The test began in August 1971. A total of 383 electric-powered vehicles were used. The majority of the vehicles were converted AM General Jeeps. The results of the test will be included in the electric vehicle performance data section of this thesis. [Ref. 3:p. 630]

2. Vehicle Description

The basic electric vehicle drivetrain consists of a battery, a controller, a motor, a transmission, and a differential layed out in accordance with the following schematic.

Battery---Controller---Motor---Transmission---Differential

The battery is the source of all the propulsion energy. The controller regulates the power supplied to the motor. The motor converts the power into rotary motion which the transmission matches to that of the axle. Finally, the differential balances the power supplied to each of the drive wheels. [Ref. 4:p. 20]

a. The Battery

The Noyes Data Corporation in their 1979 book, Electric and Hybrid Vehicles, states:

> Batteries represent only 10 percent of the initial cost of today's electric vehicle, yet the ultimate

> operating costs of electric vehicles are heavily dependent on battery performance. The energy and power available from a battery directly affect the road performance of an electric vehicle. The cycle life and maintenance requirements contribute directly to the ultimate operating cost, and the complexity of the battery system is directly related to reliability. [Ref. 3:p. 347]

The most widely used type of battery is the lead-acid battery similar to that used in gasoline-powered vehicles. While there are other types of batteries such as nickel-zinc and nickel-iron, the lead-acid battery is the most popular and will be the battery on which test results and cost data are based.

There are four types of lead-acid batteries. The starting, lighting, and ignition lead-acid battery is the battery used in gasoline-powered vehicles. Another type of lead-acid battery is the type used in most electric-powered golf cars. The final two types of lead-acid batteries are the semi-industrial and industrial. [Ref. 3:p. 350]

The starting, lighting, and ignition battery is designed to deliver high power for short periods of time. The golf car battery is designed to deliver high power for relatively long periods of time while minimizing the battery weight. The semi-industrial and industrial batteries are not so much concerned with the weight of the battery as they are the length of time the battery can deliver a high amount of power. Based on its size and low weight, the golf car

battery is the type of lead-acid battery most used in electric-powered sedans and small vans. [Ref. 3:p. 350]

The deep-discharge life cycle of a battery determines the useful life of a battery. For a golf car battery, the deep-discharge life cycle is estimated at 200 to 400 cycles. For purposes of determining the life cycle cost of the electric-powered vehicle, the deep-discharge life of the golf car battery will be fixed at 300 cycles. [Ref. 3:p. 351]

The performance of the battery is greatly affected by its operating environment. The battery capacity of a battery at 32 degrees F is only 60% of that of a battery at 72 degrees F. Thus, the cold weather performance level of an electric-powered vehicle will be much lower than its warm weather performance level. Range of the vehicle and its acceleration will be reduced due to the lower battery capacity. [Ref. 3:p. 358]

The recharging of a lead-acid battery usually takes between four and twelve hours. Overcharging of batteries can lead to loss of water in the battery, requiring additional maintenance and its accompanying costs. Undercharging of the battery results in reduced range. The controlling of the charging of the battery is usually done by the battery charger. Present day chargers are not capable of adjusting the charging period of a battery based

on temperature or the age of the battery. [Ref. 3:pp. 363-364]

b. The Controller

The controller acts as the link between the battery and the motor. It allows the electric vehicle operator to control the amount of power which flows from the battery to the motor. The controller should provide the following:

(1) Smooth operation at and near zero speed for good maneuverability and parking
(2) Smooth acceleration at the operator selected rate to the desired speed
(3) Operation at any operator-selected constant speed
(4) Smooth deceleration where regenerative braking is employed
(5) Efficient, safe, and reliable operation
(6) Overload protection for motors, motor reversing, and charging of auxiliary batteries. [Ref. 3:p. 171]

Since all current electric vehicles use direct current (DC) motors, the controller varies the voltage and the current to the motor in order to control the flow of power. [Ref. 3:p. 171]

The regenerative braking mentioned in (4) above is a means of charging the battery through the use of the energy loss which occurs when the vehicle brakes. In most conventional vehicles friction brakes are used. The kinetic energy loss resulting from braking a conventional vehicle is lost in the form of heat. In the electric vehicle, the kinetic energy loss can be recovered electrically and used to charge the battery, thus extending the range of the vehicle. In regenerative braking, the electric vehicle's

motor acts as a generator sending a charge to the battery and a resistive load to the wheels thus braking the vehicle. The controller must be able to control the amount of charge flowing to the battery if regenerative braking is used in the electric vehicle. [Ref. 5:p. 149]

c. The Motor

The direct current (DC) motor is the most popular type of motor used in an electric vehicle mainly due to the types of demands placed on an electric vehicle. The DC series motor delivers a high torque per ampere ratio under heavy loads thus reducing the battery drain of the electric vehicle during acceleration or climbing hills. [Ref. 3:p. 169]

d. The Transmission

If the only means of varying the motor speed and torque of the electric vehicle were the controller, the electric vehicle would be unable to operate efficiently. The transmission allows the electric vehicle to maximize the power and the efficiency of the electric motor. It provides better vehicle acceleration and hill climbing ability. [Ref. 3:p. 161]

The most common type of transmission used in electric-powered vehicles is the manual shift multi-gear transmission. The popularity of the manual transmission is mainly due to its size, durability, efficiency, and low price. [Ref. 3:p. 165]

Another popular transmission is the automatic shift transmission whose shift points are designed to coincide with the motor's characteristics. The main disadvantages of this type of transmission are its higher cost and weight, and its lower efficiency when compared to the manual multi-gear transmission. [Ref. 3:p. 165]

The Continuously Variable Transmission (CVT) is a transmission option which is currently being developed by electric vehicle manufacturers. Its yet to be realized goals are to offer the advantages of a fully automatic transmission with the energy efficiency of a manual multi-gear transmission. [Ref. 5:pp. 176-178]

e. The Differential

The differential is used to equally distribute the load to the drive wheels when they rotate at different speeds as in cornering. The differentials used in all the current electric-powered vehicles are the conventional differential found in gasoline-powered vehicles. [Ref. 3:p. 159]

3. Advantages of Electric-Powered Vehicles

The following are the claimed advantages of using an electric-powered vehicle.

1. Increased Reliability. The long life and simplicity of electric vehicle components will lead to more reliability and lower probability of breaking down. While most tests have actually found that electric vehicles are no more reliable than gasoline-powered vehicles, some electric vehicle proponents believe that if production of electric vehicles were

increased, the reliability benefit would be realized. [Ref. 4:p. 212]

2. Low Maintenance. Scheduled and unscheduled maintenance will be reduced by as much as two-thirds of that required to be performed on gasoline-powered vehicles. [Ref. 4:p. 212]

3. Less Dependence on Oil Imports. Since an electric vehicle does not use gasoline, an increase in the use of electric-powered vehicles would lower our requirement for oil.

4. Less Pollution. Since electric vehicles do not burn gasoline there will be less pollution.

5. Less Noise. Electric-powered vehicles are quieter than gasoline-powered vehicles. [Ref. 5:p. 8]

4. Disadvantages of Electric-Powered Vehicles

The following are the disadvantages associated with using an electric-powered vehicle.

1. Lower Performance. The range of an electric-powered vehicle is much lower than that of the gasoline-powered vehicle. The maximum cruising speed and acceleration rate of electric vehicles are also lower than those of the typical gasoline-powered vehicle. [Ref. 4:p. 213]

2. More Expensive. The initial procurement cost and the total life cycle cost of an electric vehicle is higher than that of a comparable size gasoline-powered vehicle based on current fuel and maintenance costs. [Ref. 4:p. 214]

5. Electric-Powered Vehicle Performance Data

The performance measures which will be addressed in this thesis are, first, range between chargings and, secondly, maximum cruising speed. These two performance measures will be used to classify the electric-powered vehicle as either a high or low performance vehicle.

The range of the electric-powered vehicle is a function of the speed the vehicle is traveling and the load placed upon it. The environment that the vehicle operates in, the skill of the operator, and the vehicle's condition also greatly affect the range of the vehicle.

The following test results are derived from data reported by Noyes Data Corporation in its book Electric and Hybrid Vehicles. Tests were conducted on 23 electric-powered vehicles ranging in size from a two-passenger vehicle to a van.

1. Maximum Speed: Values ranged from 31 miles per hour to 56 miles per hour. The average maximum speed was 43 miles per hour. This is well below the high performance parameter of 55 miles per hour maximum cruising speed. [Ref. 3:p. 47]

2. Range at 25 miles per hour (constant speed): Values ranged from 26 miles to 117 miles. The average range at a constant speed of 25 miles per hour was 54 miles. [Ref. 3:p. 47]

3. Range at 35 miles per hour (constant speed): Only 11 out of the 23 electric-powered vehicles were able to complete this test. The values ranged from 23 miles to 88 miles. The average range at a constant speed of 35 miles per hour was 47 miles. [Ref. 3:p. 47]

4. Range at 45 miles per hour (constant speed): Only five out of the 23 electric vehicles were able to complete this test. The values ranged from 25 miles to 71 miles. The average range at a constant speed of 45 miles per hour was 38 miles. [Ref. 3:p. 47]

Several tests were conducted to find the range of electric-powered vehicles under stop and go driving conditions. These tests were conducted in accordance with schedules written by the Society of Automotive Engineers in SAE J227a, Electric Vehicle Test Procedure, dated February

1976. Each test was terminated when the test vehicle's acceleration was insufficient to reach the required cruising speed within the required time, although the vehicle could continue to operate. [Ref. 3:pp. 39-41]

1. The first test simulated a fixed route in an urban setting. The distances traveled until the next test was terminated, ranged from 20 miles to 80 miles. The average distance was 38 miles. [Ref. 3:pp. 41,47]

2. The second test simulated a variable route in an urban setting. Twelve of the 23 vehicles were able to complete this test. The distances traveled ranged from 20 miles to 77 miles. The average distance was 36 miles. [Ref. 3:pp. 41,47]

The second stop and go driving test will be used to judge overall vehicle range as it best approximates a typical driving environment on a Navy base or station.

Based on the test results, the electric vehicle must be classified as a low performance vehicle for both maximum cruising speed and range reasons. The maximum cruising speed is, on average, 43 miles per hour with 45 miles per hour attainable on 5 out of 23 models tested. The range is limited to about 36 miles between charges.

6. Electric-Powered Vehicle Cost Data

The cost data this thesis will review pertains to initial procurement cost, fuel cost per mile of operation, maintenance cost per mile of operation, battery replacement cost, and battery charger cost.

A 1977 survey of manufacturers of electric vehicles in the United States found that the initial procurement cost of an electric vehicle ranged from $3300 to $10,800. The

cost of the electric vehicle was found to be roughly proportional to its weight ($4 to $6 per kilogram). In comparison, a gasoline-powered vehicle costs roughly $3 per kilogram. This means that an electric vehicle's initial procurement cost is anywhere from 34% to 100% higher than that of a gasoline-powered vehicle. [Ref. 3:p. 93]

In doing life cycle cost estimates of electric-powered vehicles for this thesis, it will be assumed that the initial procurement cost is 1.5 times the average cost of a gasoline-powered vehicle. The salvage value of the electric vehicle is estimated at six percent of its procurement cost. The salvage value is based on the scrap metal value of the vehicle. [Ref. 6]

Fuel estimates for electric vehicles used by the United States Postal were between 1.2 and 1.5 kilowatt hours per mile of operation [Ref. 7:p. 739]. An electric-powered vehicle requires approximately 40 kWh per battery recharge [Ref. 5:p. 249]. Based on this refueling measure, the fuel cost estimate per mile of operation can be derived by:

1. Dividing 40 kWh by the range of the electric-powered vehicle. Based on the earlier test range of 36 miles, the fuel estimate per mile of operation is:

$$\frac{40 \text{ kWh}}{36 \text{ mi}} = 1.11 \text{ kWh per mile}$$

2. Then multiply the fuel estimate per mile times the cost of a kWh of electricity.

The primary maintenance cost of electric-powered vehicles is battery maintenance. The time required to

conduct battery maintenance is dependent on the number of batteries, how hard it is to get them to conduct maintenance, and the size of the batteries. Maintenance costs also depend on how the batteries are being charged. Overcharging leads to loss of battery fluid which requires more than normal maintenance.

William Hamilton, in his article, "Costs of Electric Vehicles in Local Fleet Service," states that the maintenance costs of electric-powered vehicles will be 65% of the current cost to maintain gasoline-powered vehicles. He derives this figure by determining what percent of a gasoline vehicle's maintenance cost is directly attributable to the internal combustion engine components of the vehicle. [Ref. 7:pp. 739-740]

Further research has found no better means of estimating maintenance costs, therefore Mr. Hamilton's estimating tool of 65% will be used to figure the maintenance cost per mile of operation.

The battery replacement cost for golf car type batteries in 1979 was $50 per kWh [Ref. 3:p. 356]. Assuming that the electric vehicle is using a 40 kWh battery, the cost of replacing the battery would be $2000 in 1979 dollars. The life of the battery in terms of miles can be figured in the following manner. It was assumed earlier that a battery's deep cycle life was 300 cycles. The range of the vehicle per cycle is 36 miles. Therefore, the life

of the batteries in terms of miles is 10,800 miles, 36 miles per cycle x 300 cycle battery life. An experimental battery constructed with nickel-zinc has attained a cycle life of 100 cycles. If the battery can be mass produced, the cost per kWh is estimated to be $50 in 1979 dollars. [Ref. 5:p. 216]

According to Department of Energy studies, the range in the cost of battery chargers for electric-powered vehicles was $550 to $1300 in 1986. The more expensive battery chargers offered options such as timers. The average cost of a battery charger was estimated to be $650. The expected life of the battery charger was 10 years with no annual maintenance expenses forecasted. No special power requirements or installation requirements accompanied the purchase of the battery charger. [Ref. 8]

B. COMPRESSED NATURAL GAS-POWERED VEHICLES

1. Background

The first practical natural gas power engine was invented by Nicholas Otto in 1976, nine years before Karl Benz built the first internal combustion engine-powered vehicle. Since those early days, compressed natural gas-powered vehicles have proven themselves to be a safe alternative to the gasoline-powered vehicle in many countries around the world. Hundreds of thousands of compressed natural gas-powered vehicles are currently in operation in countries such as Italy, China and New Zealand.

In the United States and Canada there are approximately 30,000 compressed natural gas-powered vehicles on the road. [Ref. 9:p. 46]

One hundred thirty-five utility companies currently have compressed natural gas-powered vehicle fleets, up from only 65 utility companies in 1984. [Ref. 10:p. 49]

In 1978, the United States Congress passed the Natural Gas Policy Act which provided for gradual increases in natural gas wellhead price ceilings. The legislation was intended to tie the price of natural gas to the projected "heat equivalent" price of oil in 1985. By 1985, the majority of the natural gas industry was to be decontrolled. With the rapid rise of oil prices which occurred in the late 1970s and early 1980s, the projected prices for natural gas in 1985 were quickly exceeded [Ref. 11:p. ix]. In 1986, the price of oil dropped and with it the price of natural gas also decreased. By early 1987, the price of oil had begun to rise drawing the price of natural gas higher also. The parallel change in price of both oil and natural gas its attributable to the fact that they are substitutes for each other. A rise in the price of oil will cause demand for the natural gas to increase thereby causing an increase in the price of natural gas.

Since 1978, the percentage increase in the price of natural gas has exceeded the percentage increase in the price of gasoline. In 1978, the Consumer Price Index for

natural gas was 263.1 and the CPI for gasoline was 196.3. By 1984, the CPI of natural gas had risen to 584.4, while the CPI of gasoline had risen to 370.2. [Ref. 12]

2. Vehicle Description

The compressed natural gas vehicle which has proved to be the most popular with the general public is actually a conversion of a standard gasoline-powered vehicle to a dual fuel capable vehicle. Most gasoline-powered vehicles can be converted to the compressed natural gas system in one day or less. The conversion process does not require any major engine modifications. All the conversion parts simply bolt on. With the conversion kit installed the vehicle operator can drive the vehicle using compressed natural gas fuel or gasoline. The switchover procedure from one fuel to the other is a simple flip of a switch. [Ref. 13]

The compressed natural gas conversion kit includes the following parts: compressed natural gas cylinders, fuel selector switch, regulator, fuel gauge transducer, filling connection, gasoline solenoid valve, dual curve ignition box, mixer, fuel gauge, master shut off valve, and gas tubing. The following diagram, Figure 1, shows the major parts, their functions, and their installed locations in a typical sedan. [Ref. 14:p. 3]

The natural gas cylinders hold natural gas at a pressure of 2400 pounds per square inch. Due to the high pressure of the gas, no fuel pump is required to deliver the

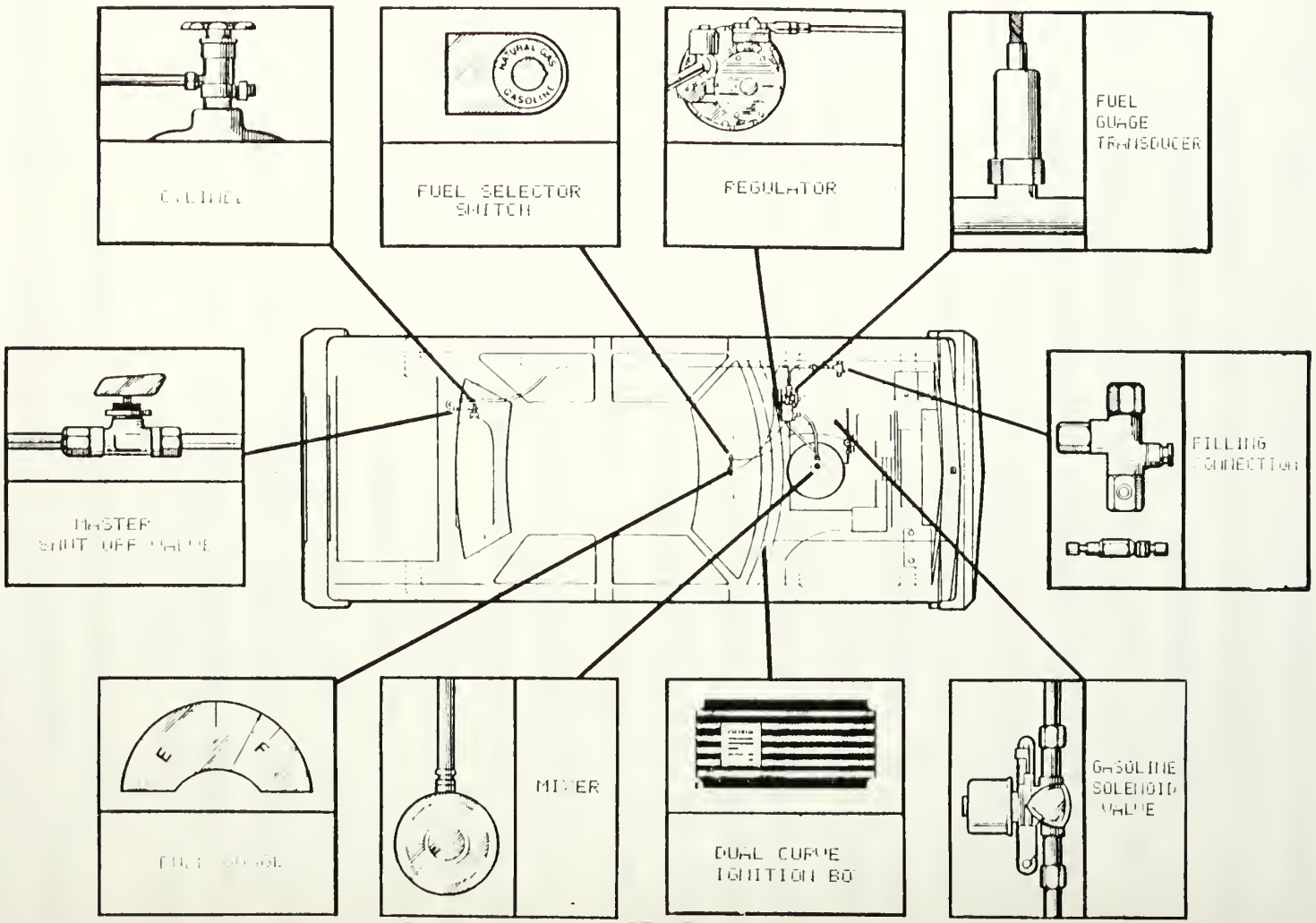

Figure 1. Conversion Components

fuel to the mixer. The regulator controls the flow of natural gas from the cylinder(s) to the mixer. The mixer bolts onto the carburetor and insures the proper mix of natural gas and air is fed into the carburetor and the engine. The dual curve ignition box adjusts the ignition timing to correspond to the fuel, gasoline or natural gas, being fed into the carburetor. The fuel selector switch allows the vehicle operator to switch the fuel source of the vehicle without stopping the vehicle. The fuel selector switch is located on the interior dash of the car as is an added natural gas fuel gauge which keeps the driver informed as to the amount of natural gas left in the cylinder(s). [Ref. 14:p. 3]

3. Advantages of Compressed Natural Gas Vehicles

The following are the claimed advantages of a compressed natural gas-powered vehicle.

a. Natural gas is cheaper per gallon equivalent than gasoline. The American Gas Association estimates that it is 30 to 60% cheaper to refuel a car with compressed natural gas than with gasoline. The present cost of a gallon equivalent of natural gas is between 45 cents and 85 cents. [Ref. 14:p. 1]

b. Natural gas burns cleaner than gasoline thus producing less pollution. Natural gas burns lead-free and produces almost no carbon monoxide. [Ref. 14:p. 1]

c. Natural gas reduces the maintenance required on vehicles. Standard maintenance on vehicles that burn natural gas is half that of gasoline-powered vehicles. [Ref. 14:p. 1]

d. Natural gas is plentiful. Consumers don't have to worry about any shortage of natural gas in the foreseeable future. [Ref. 14:p. 2]

e. Natural gas is safer than gasoline. Compressed natural gas cylinders are built to withstand abuse, unlike the conventional vehicle gasoline tank. In the event of a gas leak, natural gas, being lighter than air, will dissipate rather than pool like gasoline. The combustion point of natural gas is 1300 degrees F while the combustion point of gasoline is much lower, 800 degrees F. [Ref. 9:p. 46]

4. Disadvantages of Compressed Natural Gas Vehicles

The following are the disadvantages associated with converting a vehicle to compressed natural gas.

a. Few natural gas refueling stations. There are only 250 private refueling stations and five public refueling stations located in the United States. [Ref. 9:p. 49]

b. Limited range with natural gas as fuel. A typical compressed natural gas cylinder holds enough fuel to allow a range of between 40 to 90 miles. However, with the dual fuel capability extended trips can be made with a compressed natural gas converted vehicle. [Ref. 9:p. 48]

c. Lower performance. The compressed natural gas-powered vehicle loses approximately 10% of its horsepower when it operates on natural gas rather than gasoline. [Ref. 9:p. 48]

d. High fixed cost to convert vehicle fleet. In order to have the ability to refuel a fleet of vehicles, a company would have to purchase a cascade compressor and its attendent filling station. This capital outlay is the most expensive aspect of converting a vehicle fleet to compressed natural gas. [Ref. 9:p. 48]

e. Due to the installation of compressed natural gas cylinders in the trunk or storage compartment of the vehicle, the cargo capacity of the vehicle is reduced.

5. Compressed Natural Gas Vehicle Performance Data

The range of a compressed natural gas-powered vehicle while operating on natural gas is a function of the number of gas cylinders installed in the vehicle. Each gas

cylinder allows a range of between 40 and 90 miles, depending on the size of the cylinder. However, the dual fuel capability of the compressed natural gas-powered vehicle allows it to be used for any trip that a conventional gasoline-powered vehicle can make. For this reason, the compressed natural gas vehicle is considered a high performance vehicle in the range performance area.

The use of compressed natural gas as a fuel results in a 10% decrease in the power of the converted internal combustion engine vehicle. While this loss of power affects acceleration, it can be assumed that all converted vehicles are capable of attaining the 55 miles per hour maximum cruising speed needed to qualify as a high performance vehicle in the cruising speed performance area.

Based on the range and maximum cruising speed of the compressed natural gas-powered vehicle, it is classified as a high performance vehicle.

6. Compressed Natural Gas Vehicle Cost Data

The initial procurement cost of a compressed natural gas-powered vehicle is the sum of the average cost of a gasoline-powered vehicle and the average cost of the conversion kit. In 1984, the average cost to convert a sedan to natural gas for 120 U.S. gas utility company vehicle fleets was approximately $1,521, while the average cost to convert a van or small truck to natural gas was $1,589 [Ref. 15:p. 22]. The average of these two

installation costs is $1,555. The 1986 adjusted cost of installation, using the adjustment factors in Table 1, is $1,628 ((1555/311.1) x 325.7). Therefore, the initial procurement cost of the vehicle used in this thesis is:

Average cost of gasoline vehicle + $1,628

While the installation of the conversion kit adds some value to the vehicle, the salvage value will be estimated at 10% of the initial procurement cost of the gasoline-powered vehicle before conversion took place.

Since this thesis is concerned with fleet vehicles, a decision to convert to compressed natural gas-vehicles would require the purchase of a cascade compressor and filling station. A 30 cubic foot per minute (CFM) cascade compressor refueling system, capable of refueling 30 vehicles at a time, would cost $75,000 [Ref. 16:p. 8]. In 1982, a cascade compressor and filling station capable of refueling nine vehicles per hour would cost approximately $44,000 installed [Ref. 6:pp. 56,57]. A small compressor capable of handling one or two vehicles per hour would cost around $7,000 installed [Ref. 14:p. 7]. The small compressor would take too long to refuel vehicles while the 30 CFM compressor would probably exceed the refueling requirements of most Navy commands. Therefore, the investment cost for the compressor and filling station used

in this thesis will be the $44,000 option adjusted to 1986 dollars (i.e., $49,570).

As of 28 February 1986, the national average price for a gallon equivalent of natural gas was 93 cents. The cost of natural gas to vehicle fleet users was $0.72 on a national average basis. The average small truck or van will get around 15 miles per gallon. Therefore, the average cost of fuel per mile of operation for a compressed natural gas-powered vehicle is approximately five cents for fleet users. [Ref. 16:p. 2]

The American Gas Association claims that the maintenance costs of compressed natural gas-powered vehicles is half that of gasoline-powered vehicles [Ref. 14:p. 1]. This claim is based on the fact that natural gas is a clean burning fuel so oil, spark plugs, and points will not require changing as often as in a gasoline-powered vehicle. In Mr. Hamilton's review of internal combustion engine maintenance costs, he found that the ignition system maintenance costs and the lubrication costs amounted to roughly 14% of the total maintenance cost of an internal combustion engine vehicle [Ref. 7:p. 740]. Therefore, an extension of the life of the oil, spark plugs, and points to double their normal life would only result in a savings of 7% of the maintenance cost. For the purposes of this thesis, the maintenance cost of natural gas vehicles will be

estimated at 75 percent of the maintenance cost of gasoline-powered vehicles.

The conversion kit's useful life is at least equal to the life of the vehicle in which it is installed [Ref. 6:p. 57]. The American Gas Association estimates the useful life of the compressor to be 10 years with annual operations and maintenance expenses for the compressor being equal to 12 cents per gallon equivalent of natural gas pumped [Ref. 17].

III. THE LIFE CYCLE COST MODEL

Department of Defense Instruction 7041.3, dated 18 October 1972, defines economic analysis as:

> A systematic approach to the problem of choosing how to employ scarce resources and an investigation of the full implications of achieving a given objective in the most efficient and effective manner.

The instruction goes on to require an economic analysis be performed for proposals whenever there is a "choice or trade-off between two or more options even when one of the options is to maintain the status quo or to do nothing." [Ref. 18:pp. 2-3]

A major portion of the economic analysis is the cost analysis. DOD Instruction 7041.3 requires that life cycle cost estimates be prepared for all program alternatives when feasible. The instruction defines life cycle costs to include "all anticipated expenditures directly or indirectly associated with an alternative." The instruction specifically states that "sunk costs," costs which have already been incurred prior to conducting the analysis, are excluded from the cost analysis. [Ref. 18:p. 2]

The life cycle cost estimate begins with an estimate of outlays for each year of the "economic life" of the alternative. The economic life of an alternative is the period of time that an alternative is capable of providing the service it was designed for. [Ref. 18:p. 7]

Once the yearly outlay estimates have been made, a discount factor is applied to each year's outlays to determine the net present value of the alternative. The discount factor is used to recognize that there are differences in the timing of expenditures. A dollar spent today is more valuable than a dollar that will be spent two years from today. [Ref. 18:pp. 5-6]

In the civilian business environment, the discount factor is based on the cost of acquiring additional capital. In the Department of Defense, the discount factor is based on a 10% interest rate. The discount factors for the Department of Defense are listed in Table 2. [Ref. 18:p. 6]

TABLE 2

DEPARTMENT OF DEFENSE DISCOUNT FACTORS

Present Value of $1

Project Year	10% Discount Factor
1	0.954
2	0.867
3	0.788
4	0.717
5	0.652
6	0.592
7	0.538
8	0.489
9	0.445
10	0.405

Source: Department of Defense Instruction 7041.3, dated 18 October 1972.

The alternative which is found to have the lowest average cost per year is considered to be the most efficient. [Ref. 18:p. 7]

A. LIFE CYCLE COST COMPONENTS

The major groups of costs which can be included in a life cycle cost estimate are:

1. Research and development costs
2. Investment costs
3. Operations costs. [Ref. 18:pp. 2-5]

The Department of Defense has not invested funds in the research and development of either electric-powered vehicles or compressed natural gas-powered vehicles, so research and development funds will not be entered into the life cycle cost formula.

Investment costs are costs associated with the purchase of real property, equipment, non-recurring services or operations, and maintenance start-up costs. Investment costs do not necessarily occur in only Year 1 of a procurement.

Investment costs can be either fixed or variable. Fixed investment costs equate to fixed costs in the civilian business environment as they are the fixed cost of choosing a particular alternative. Being a fixed cost, the amount does not vary with units of production, or in the case of this thesis, vehicles in a particular fuel category. An

example of a fixed investment cost would be a refueling station. [Ref. 19:p. 72]

Variable investment costs are tied to the volume of an option. An example of a variable investment cost is the initial procurement cost of a vehicle. The variable investment cost rises with each vehicle procured. [Ref. 19:p. 74]

Operations costs, or recurring costs, are costs such as personnel, material consumed during operations, overhead, operating expenses and other annual expenses. The choice of either of the alternative vehicles for use in the fleet would not necessitate any additional personnel or overhead. The recurring cost affected would be material consumed, mainly fuel and maintenance costs. [Ref. 18:pp. 4-5]

Recurring costs such as fuel and maintenance costs are classified as variable costs by civilian businesses in that they vary directly with the units of output or, in the case of this thesis, the number of vehicles in a particular fuel category. Another common business term for variable costs is direct costs. [Ref. 19:p. 74]

B. LIFE CYCLE COST FORMULA

The following life cycle cost formula was presented by Dr. Dan Boger of the Naval Postgraduate School at the Defense Logistics Agency Operations Research and Economic Analysis Workshop in Virginia Beach, Virginia, on 6 December 1985. The title of Dr. Boger's presentation was

"Alternative Vehicle Propulsion and the Optimal Industrial Fleet." [Ref. 20]

$$LCC_{ij} = f_{ij} + c_{ij}x_{ij}$$

where:

i = vehicle type

j = propulsion type

LCC_{ij} = life cycle cost for alternative i,j

f_{ij} = fixed investment for alternative i,j

c_{ij} = unit variable LCC for alternative i,j

x_{ij} = number of units of alternative i,j.

The formula gives the user the option to deal with various types of vehicles. Due to data limitations at the Naval Postgraduate School Transportation Office, this thesis will deal only with different types of propulsion, therefore the i variable will not change.

The total life cycle cost formula is broken down into two sub-formulas. The first sub-formula is used to compute the unit variable life cycle cost for the alternative i,j.

$$c_{ij} = p_{ijo} + \sum_{t=1}^{T} o_{ijt}\delta^{t} - \delta^{T}s_{ij}$$

where:

p_{ijo} = unit procurement cost of alternative i,j

o_{ijt} = unit operating cost of alternative i,j in year t

δ^t = discount factor in year t

s_{ij} = unit salvage value for alternative i,j

T = the number of years in the economic life of the vehicle.

The second sub-formula is used to calculate the unit operating cost of alternative i,j in year t.

$$o_{ijt} = m_{it}(e_{jt} + n_{ijt}) + p_{ijt}$$

where:

m_{it} = annual miles for vehicle type i in year t

e_{jt} = cost/mile for fuel of type j in year t

n_{ijt} = maintenance cost/mile for alternative i,j in year t

p_{ijt} = unit procurement costs for alternative i,j in year t.

C. GASOLINE-POWERED VEHICLE LIFE CYCLE COST

The best way to explain the use of the life cycle cost formula and its sub-formula is through an example. The gasoline-powered vehicle will be classified as propulsion type 1. The following data were gained through a review of the 1986 records of the transportation office of the Naval Postgraduate School [Refs. 21,22].

1. Number of vehicles subject to study: 62
2. Total initial procurement (investment) cost of subject vehicles in 1986 dollars: $506,274
3. Total miles driven by subject vehicles in 1986: 313,000
4. Total fuel cost for subject vehicles in 1986: $17,557

5. Total maintenance cost for subject vehicles in 1986: $27,363

6. Estimated average economical life for subject vehicles: 8 years

7. Estimated average salvage value for subject vehicles: 10% of initial procurement cost.

Using the above data, the life cycle cost for gasoline vehicles at the Naval Postgraduate School is computed as follows:

1. Beginning with the sub-formula for unit operating cost of alternative i,1 in year t, computations are as follows:

   a. Annual miles for vehicle type i in year t (m_{it})

$$\frac{313,000}{62} = 5048 \text{ miles}$$

   b. Cost/mile for fuel of type 1 in year t (e_{1t})

$$\frac{17,557}{313,000} = \$0.0561$$

   c. Maintenance cost/mile for alternative i,1 in year t (n_{ilt})

$$\frac{27,363}{313,000} = \$0.0874$$

   d. There are no unit procurement costs in any year other than year 0 so $p_{ilt} = 0$.

      Using the figures computed above the unit operating cost of gasoline vehicles in year t is:

$$o_{ilt} = 5048(.0561 + .0874) + 0 = \$724$$

2. The next step is to compute the unit variable life cycle cost for the gasoline alternative (c_{i1}).

a. The initial unit procurement cost of gasoline vehicles in year 0 (p_{i10}) is:

$$\frac{506,274}{62} = \$8,166$$

b. Next, the unit operating cost computed previously is multiplied by the discount factors for years one through eight, its economic life. The products are then added together to get the total discounted operating cost for the economic life of the vehicle.

$$\sum_{t=1}^{T} o_{i1}{}^{t}\delta^{t} = ((724 \times .954) + (724 \times .867) + (724 \times .788) \ldots + (724 \times .489))$$

$$= \$4,053$$

The total discounted fuel cost was $1,584, while the discounted maintenance cost was $2,469.

c. The unit salvage value is the estimated salvage value of the vehicle times the discount factor in the year it is salvaged. The gasoline-powered vehicle has an eight year economic life with a salvage value of 10% of its initial procurement cost. The initial procurement cost was $8,166, so its salvage value is $817 x .489, the discount factor in year eight. Therefore,

$$\delta^{T}s_{i1} = \$400$$

Putting the above computations into the formula, the unit variable life cycle cost for the gasoline-powered vehicle equals:

$$8,166 + 4,053 - 400 = \$11,819$$

3. The final step in computing the life cycle cost for the gasoline vehicle alternative is to figure out the fixed investment costs for the alternative and the number of vehicles using gasoline. The fixed investment cost of choosing gasoline equals zero.

This is due to the prior purchase of all the equipment and facilities required to maintain and operate the gasoline vehicles. These prior expenditures are now considered "sunk costs" and are excluded from the cost analysis. The number of vehicles using gasoline in the optimal solution is unknown. Thus the final life cycle cost formula for the gasoline-powered vehicle option is:

$$0 + 11{,}819x_{i1}$$

D. ELECTRIC-POWERED VEHICLE LIFE CYCLE COST

The life cycle cost for the electric-powered vehicle will be derived by using the cost data that were determined in Chapter II. The electric-powered vehicle will be classified as propulsion type 2.

The computations for the unit operating cost of the electric-powered vehicle in year t are as follows:

1. Annual miles for vehicle type 2 are the same as the gasoline-powered vehicle, 5048 miles.

2. The fuel efficiency rating of the electric vehicle is 1.11 kilowatt hours per mile of operation. The cost to the Naval Postgraduate School for a kilowatt hour of electricity is roughly $0.08, according to the Public Works Office. Therefore, the cost/mile for fuel is:

$$1.11 \times .08 = \$0.0888$$

3. It was decided in Chapter II that the maintenance cost of the electric vehicle would be estimated at 65% of the maintenance cost of the gasoline-powered vehicle. The gasoline-powered vehicle maintenance cost per mile was determined to be $0.0874. Therefore, the maintenance cost per mile of operation for the electric-powered vehicle is:

$$.65 \times .0874 = \$0.0568$$

4. Due to the 10 year economic life of the battery charger it will not have to be replaced during the life of the vehicle. The batteries have an estimated life of 10,800 miles. Based on the average annual miles of 5048, the batteries would require replacement every 2.14 years or roughly every two years. The replacement cost was estimated to be $2,000 in 1979, this equates to $2996 in 1986, based on the "All Items" consumer price index in Table 1. Battery replacement expense of $2,996 should be expected in years 3, 5, 7, and 9 of the analysis. If the experimental nickel-zinc batteries are perfected, the batteries would have to be replaced every seven years at a replacement cost of $2,980.

Putting the above data into the unit operating cost formula, the unit operating cost for an electric-powered vehicle in years 1, 2, 4, 6, 8, and 10, is determined to be:

$$5048(.0888 + .0568) + 0 = \$735$$

In years 3, 5, 7, and 9, the unit operating cost for an electric-powered vehicle is found to be:

$$5048(.0888 + .0568) + 2,996 = \$3,731$$

The unit variable life cycle cost for the electric vehicle is computed as follows:

1. The initial procurement cost of the electric vehicle was estimated to be 1.5 times the initial procurement cost of the gasoline-powered vehicle. The initial procurement cost of the gasoline-powered vehicle was determine to be $8,166. Therefore, the initial procurement cost of the electric-powered vehicle is:

$$1.5 \times 8,166 = \$12,249$$

This initial procurement cost includes a battery charger.

2. The unit operating cost for the electric vehicle ($735) is multiplied by the discount factors for each applicable year (1, 2, 4, 6, 8, 10) and the unit operating cost including battery replacement ($3731) for years 3, 5, 7, and 9, is multiplied by the appropriate discount factors. For years 1, 2, 4, 6, 8, and 10, the computations would be:

((735 x .954) + (735 x .867) + (735 x .717) +
(735 x .592) + (735 x .489) + (735 x .405))

The sum of these products is $2,956. For years 3, 5, 7, and 9, the computations are:

((3731 x .788) + (3731 x .652) + (3731 x .538)
+ (3731 x .445))

The sum of these products is $9,039. The sum total for all the years of the electric vehicle's economic life is $11,995. Of this total, fuel cost amounts to $2,886, and maintenance, which includes replacing the batteries, amounts to $9,109.

3. The salvage value of the electric-powered vehicle was estimated to be six percent of the initial procurement cost of the vehicle. Therefore, the unit salvage value equals ((12,249 x .06) x .405) = $298.

By inserting the above computations into the unit variable life cycle cost formula, the ten year unit life cycle cost for the electric vehicle is determined to be:

12,249 + 11,995 - 298 = $23,946

To find the eight year life cycle cost, the ten year unit life cycle cost is divided by 10, then the quotient is multiplied by eight. The resulting eight year unit life cycle cost is $19,157. The eight year unit life cycle cost for fuel would be $2,309, with the eight year unit life cycle cost for maintenance totalling $7,287.

The next step is to compute the life cycle cost for the electric-powered vehicle alternative. Here the cost of making the decision to use electric-powered vehicles is recognized. The cost of making the decision is equal to the cost of procuring the vehicles plus the cost of procuring support equipment or facilities.

The cost to procure a battery charger is included in the vehicle procurement cost. No special facilities are required as the battery charger can run off standard electric current of 110 volts. Therefore, the life cycle cost formula for the electric-powered vehicle alternative is:

$$0 + 19{,}157x_{i2}$$

E. COMPRESSED NATURAL GAS-POWERED VEHICLE LIFE CYCLE COST

The compressed natural gas-powered vehicle will be classified as propulsion type 3. Its life cycle costs will computed using the cost figure derived in Chapter II.

The unit operating cost of alternative i,3 in year t is computed as follows:

1. Annual miles for the vehicle type is 5048 miles.
2. The fuel cost per mile is $0.05.
3. The maintenance cost per mile was estimated to be 75% of the gasoline vehicle, .0874 x .75 = .066.
4. The only unit procurement costs occur in year 0. Therefore, the unit operating cost of a compressed natural gas-powered vehicle in year t =

$$5048\ (.05 + .066) + 0 = \$586.$$

The unit variable life cycle cost for the compressed natural gas-powered vehicle is computed below:

1. The initial procurement cost of the compressed natural gas vehicle was estimated to be the initial procurement price of a gasoline-powered vehicle plus $1,628. Therefore, the initial procurement cost of a compressed natural gas vehicle is:

$$8,166 + 1,628 = \$9,794.$$

2. The sum total of the compressed natural gas vehicle's unit operating cost of $586 times the discount factors in its eight year economic life is $3,280. The fuel cost portion of this total is $1,410, while maintenance costs amount to $1,870 during the eight year economic life.

3. The salvage value of $817 times the discount factor in year eight of .489 yields a unit salvage value of $400, the same as that of the gasoline-powered vehicle.

Putting the above computations into the life cycle cost formula, the life cycle cost for the compressed natural gas-powered vehicle is determined to be:

$$9,794 + 3,280 - 400 = \$12,674$$

The life cycle cost for adopting the compressed natural gas vehicle into the Naval Postgraduate School vehicle fleet would be the fixed investment cost of building and equipping a compressed natural gas refueling station plus the variable life cycle cost of a compressed natural gas vehicle times the number of compressed natural gas vehicles in the fleet. The compressed natural gas refueling station was determined to cost $44,000 in 1982 or $49,570 in 1986 dollars.

Therefore, the life cycle cost of the compressed natural gas vehicle alternative is:

$$49,570 + 12,674x_{i3}.$$

Life cycle cost computation worksheets are included as the Appendix of the thesis.

IV. THE LINEAR PROGRAMMING MODEL

Linear programming is an advanced mathematical programming technique which has found wide use in the business environment. It deals only with problems where the relationships between the variables are linear. For example, when a vehicle is purchased a price is paid. If two of the vehicles are purchased, the purchaser would have to pay twice as much. The relationship between price and quantity in this example is a linear relationship. [Ref. 23:p. 2]

Linear programming was developed in the late 1940s by Professor G. Dantzig. It was widely used in the late 1950s by petroleum companies to determine the best mix of gasoline and heating oil the companies should produce in order to maximize their profits. Various linear programming models were developed to help the petroleum companies deal with pipeline and tanker problems. [Ref. 23:p. 2]

Linear programming provides business managers a mathematical tool to help them allocate scarce resources to achieve an objective. Some examples of objectives would be to maximize profit or minimize costs. Linear programming will find the very best solution to a given problem and it will indicate when there are equally good alternative solutions. [Ref. 23:p. 2]

The business manager uses linear programming by looking at a real world problem and describing it in a mathematical model which consists of a linear objective function and linear resource constraints. [Ref. 24:p. 25]

The three principal steps in developing a linear programming model are:

(1) the identification of solution variables (the quantity of the activity in question),
(2) the development of an objective function that is a linear relationship of the solution variables, and
(3) the determination of system constraints, which are also linear relationships of the decision variables, that reflect the limited resources of the problem. [Ref. 24:p. 26]

Due to the fixed investment that would ensue if compressed natural gas-powered vehicles were used in the fleet, the fixed charge integer linear programming model will be used in this thesis. In an integer linear program, some or all of the solution variables are required to be integers. [Ref. 25:p. vii]

Integer programming was pioneered in the late 1950s by Ralph Gomory. The advantage of an integer program is that the solution will be in integer form. With a non-integer linear program, non-integer solutions are often computed. In this thesis, a non-integer solution would not be helpful as one cannot use half a vehicle. [Ref. 25:p. vii]

In fixed charge problems, if the decision made is to go with an alternative, there is a fixed charge inherent in making that decision [Ref. 25:p. 18]. In this thesis, the fixed charge would be the cost of building and equipping the

compressed natural gas refueling station. Even before one vehicle has joined the vehicle fleet, there would be an expenditure of funds which is not a linear cost of operating the compressed natural gas vehicle.

In setting up a fixed charge model, a decision variable is put in the objective function. The decision variable has two values, 1 or 0. If the value of the decision variable is 1, the alternative is adopted and the fixed charge will be expended. If the value of the decision variable is 0, then the alternative is rejected and the fixed charge is bypassed.

A. FIXED CHARGE INTEGER LINEAR PROGRAM MODEL

In his presentation at the Defense Logistics Agency Workshop, Dr. Dan Boger explained the following integer programming model which can be used for deriving the optimal vehicle fleet. [Ref. 26]

The integer programming model is:

$$\text{minimize} \sum_i \sum_j c_{ij}x_{ij} + f_{ij}y_{ij}$$

subject to the following constraints:

$$(1) \quad \sum_i \sum_j p_{ij0}x_{ij} + f_{ij}y_{ij} \leq P_0$$

$$(2) \quad \sum_{t=1}^{t=8} \sum_i \sum_j e_{ijt}x_{ij} \leq E$$

$$(3) \quad \sum_{t=1}^{t=8} \sum_{i} \sum_{j} m_{ijt} x_{ij} \leq M$$

$$(4) \quad x_{ij} - u_{ij} y_{ij} \leq 0$$

$$(5) \quad -x_{ij} + l_{ij} y_{ij} \leq 0$$

$$(6) \quad \sum_{i} \sum_{j} x_{ij} = F$$

where:

c_{ij} = unit variable life cycle cost for alternative i,j

x_{ij} = integer number of units of alternative i,j

f_{ij} = fixed investment costs for alternative i,j

y_{ij} = decision variable for alternative i,j

p_{ij0} = unit procurement costs in year 0 for alternative i,j

e_{ijt} = fuel costs in year t for alternative i,j

E = total fuel costs for eight year life cycle for all fleet vehicles

m_{ijt} = maintenance costs in year t for alternative i,j

M = total maintenance costs for eight year life cycle for all fleet vehicles

P_0 = total investment costs in year 0

u_{ij} = upper limit on number of units of alternative i,j

l_{ij} = lower limit on number of units of alternative i,j

F = number of vehicles in vehicle fleet

The fixed charge objective function for the above integer programming model is:

$$\text{Minimize} \quad \sum_{i} c_i x_i + f_i y_i$$

where:

$x_i \geq 0$ and is an integer

$y_i = 0$ or 1

$x_i(1 - y_i) = 0$

The following budget and performance constraints were placed on the optimal vehicle mix for the Naval Postgraduate School vehicle fleet [Ref. 27]:

1. At least 30 of the 62 vehicles must be gasoline-powered in order to meet current vehicle taskings.
2. Fleet life cycle fuel expenditures must not exceed $189,000.
3. Fleet life cycle maintenance expenditures must not exceed $183,000.

Inserting the values for the variables which were computed in Chapter III and the budget and performance constraints delineated above, the vehicle mix formulation problem becomes:

$$\text{Minimize } 11819x_1 + 19157x_2 + 12674x_3 + 0y_1 + 0y_2 + 49570y_3$$

subject to

$$(1)\ 8166x_1 + 9799x_2 + 9794x_3 + 0y_1 + 0y_2 + 49570y_3 \leq 540{,}000$$

$$(2)\ 1584x_1 + 2309x_2 + 1410x_3 \leq 189{,}000$$

$$(3)\ 2469x_1 + 7287x_2 + 1870x_3 \leq 183{,}000$$

$$(4)\ x_1 - 62y_1 \leq 0$$

(5) $x_2 - 32y_2 \leq 0$

(6) $x_3 - 62y_3 \leq 0$

(7) $-x_1 - x_3 + 30y_1 \leq 0$

The first constraint is a budget constraint on the total investment cost in year 0. The constraint covers both fixed investment and variable investment costs. The right hand side value of the constraint is derived by computing a 95% confidence interval for vehicle procurement costs for the Naval Postgraduate School fleet of 62 vehicles.

The second constraint is a budget constraint on the amount of funds that can be spent on fuel during the eight year life of the fleet vehicles. The right hand side of the constraint is computed using a 95% confidence interval based on 1986 Naval Postgraduate School fuel expenditures.

The third constraint is also a budget constraint but it limits the amount of funds which can be spent to maintain the 62 vehicle fleet during its eight year life cycle. The right hand side is computed using a 95% confidence interval based on the 1986 maintenance costs for the Naval Postgraduate School fleet of 62 vehicles.

The fourth through seventh constraints are on the number of vehicles of each fuel type that may be included in the optimal fleet mix. The fourth constraint limits the number of gasoline-powered vehicles that may be included in the optimal mix to 62. The fifth constraint limits the number

of electric-powered vehicles that may be in the optimal mix to 32. This coincides with the operational requirement that at least 30 of the 62 vehicles be gasoline-powered. The sixth constraint limits the number of compressed natural gas-powered vehicles to 62. All vehicles in the optimal mix may be compressed natural gas vehicles due to their dual fuel capability. The seventh constraint insures that at least 30 of the vehicles in the optimal mix are capable of using gasoline as a fuel source.

When the above problem was run through the integer program, the optimal mix of vehicles was computed to be 62 gasoline-powered vehicles. The net present cost of purchasing, operating and maintaining these vehicles for an eight year life was computed to be $732,778.

The above integer program would be useful to the Navy Transportation Officer if he were to have control of the funds required to procure the vehicles for his command. However, the Naval Facilities Engineering Command, Chesapeake Division (ChesDiv), located in Washington, D.C., is the central procurement activity for vehicles for the Navy. Vehicles purchased by ChesDiv are sent to Navy commands, who then make decisions as to what vehicles will be retired from service. The individual command transportation officers do not have an input into the procurement process unless they require a vehicle in addition to their present allowance.

The funds required to build a compressed natural gas refueling station would be justified through a one time budget augment request consisting of a request for Other Procurement, Navy (OPN) funds and minor construction funds. The budget augment request would be filed through the command's chain of command during the annual budget cycle. The justification for these funds would be a projected savings due to the use of alternative fuels rather than gasoline in fleet vehicles.

In order to approach the optimal mix problem from the viewpoint of the individual command transportation officer, the following integer program is proposed:

Minimize $4053x_1 + 9596x_2 + 3280x_3 + 0y_1 + 0y_2 + 0y_3$

Subject to

(1) $1584x_1 + 2309x_2 + 1410x_3 \leq 189{,}000$

(2) $2469x_1 + 7287x_2 + 1870x_3 \leq 183{,}000$

(3) $x_1 - 62y_1 \leq 0$

(4) $x_2 - 32y_2 \leq 0$

(5) $x_3 - 62y_3 \leq 0$

(6) $-x_1 - x_3 + 30y_1 \leq 0$

This integer program recognizes only the funds that the individual command has control over. The objective function

consists of the life cycle fuel and maintenance costs attributable to each of the vehicle propulsion types and ignores salvage values because these funds are not returned to the command disposing of the vehicle.

The constraints are the same as the first integer program with the exception that the constraint dealing with initial investment costs is deleted since the command has no control over these funds.

The optimal mix derived from this integer program would provide the lowest cost vehicle fleet in terms of annual Operations and Maintenance, Navy funds.

When the above formulated problem is run through the integer program, the optimal solution is found to be 62 compressed natural gas-powered vehicles. The O&M,N cost of operating the 62 vehicle fleet of compressed natural gas vehicles for the eight year life of the vehicles would be $203,360.

A third situation to consider is the establishment of a new transportation fleet at a base where no refueling capabilities presently exist. The cost of building a two-pump gasoline refueling station is estimated to be $150,000 [Ref. 28]. Assuming that the experimental nickel-zinc batteries were installed in the electric vehicle, the problem would be formulated as follows:

$$11819x_1 + 14633x_2 + 12674x_3 + 150000y_1 + 0y_2 + 49570y_3$$

subject to

$$8166x_1 + 9799x_2 + 9794x_3 + 150000y_1 + 0y_2 + 49570y_3 \leq 660000$$

$$1584x_1 + 2309x_2 + 1410x_3 \leq 189000$$

$$2469x_1 + 2763x_2 + 1870x_3 \leq 183000$$

$$x_1 - 62y_1 \leq 0$$

$$x_2 - 32y_2 \leq 0$$

$$x_3 - 62y_3 \leq 0$$

$$-x_1 - x_3 + 30y_1 \leq 0$$

When the above problem was run through the integer program, the optimal vehicle mix was found to be 62 compressed natural gas vehicles. The net present cost of procuring, operating and maintaining the fleet was computed to be $835,358.

B. SUMMARY AND CONCLUSIONS

This thesis has developed and explained a model for determining the life cycle cost of alternative fuel vehicles. Using the life cycle cost and requirement data particular to a command, the integer linear program model can be used to determine the optimal mix of vehicles for the command's transportation fleet.

The thesis has looked at three ways the models can be used. The first case was that of an established base with a gasoline refueling station in operation. Due to the high cost of procuring the compressed natural gas refueling station and the high life cycle cost of the electric vehicle, the optimal solution was found to be an entire fleet of gasoline vehicles.

The second case looked at minimizing the annual operations and maintenance expenditures on the transportation fleet while ignoring the initial investment costs. The integer program found a fleet of compressed natural gas vehicles would require the least expenditure of operations and maintenance funds.

The third case looked at the problem of establishing a new transportation fleet at a base which does not have any refueling capabilities at the present time. The high cost of the gasoline refueling station more than offsets the cost of the compressor and conversion kits for the compressed natural gas vehicles. Again, the optimal solution was found to be an entire fleet of compressed natural gas vehicles.

The electric vehicle was found to have much too high a life cycle cost to enter into the optimal mix, even though it had no fixed investment cost. In the third case, the experimental batteries were factored into the life cycle cost but the reduction in life cycle cost was still too small to make the electric vehicle an economic solution.

The compressed natural gas vehicle appears to be a feasible alternative to the gasoline vehicle. The factors which seem to impair its competition with the gasoline vehicle are:

1. The scarcity of compressed natural gas refueling stations. The number of refueling stations would not be expected to increase until the number of vehicles using compressed natural gas increases.

2. The price of natural gas, a relatively abundant natural resource, is tied to the price of petroleum, an increasingly scarce natural resource, by the Natural Gas Policy Act of 1978. With this dependency on the price of oil, the price of natural gas is inflated to a level which does not justify the additional investment in conversion kits and compressed natural gas refueling stations for little or no savings will accrue.

3. The high cost of the conversion kits. The conversion kits are specialty items not offered by automobile manufacturers, thus the cost is high and the maintenance of conversion kit parts is very specialized.

The above factors are interrelated with the price of natural gas being the major obstacle in the compressed natural gas vehicle's future. If the price of natural gas can drop to a level significantly below that of gasoline, its attractiveness as a vehicle fuel will increase. Savings from lower fuel costs would justify investment expenditures by large businesses, state and local governments. This would increase the number of CNG-vehicles on the road, leading to an increase in compressed natural gas refueling stations. Increased popularity of compressed natural gas would lead automobile manufacturers to offer factory equipped CNG-vehicles. The mass production of the CNG-

vehicle would lower the additional cost for the CNG-conversion kit as well as increase the number of maintenance facilities capable of repairing CNG conversion systems.

APPENDIX

VEHICLE LIFE CYCLE COST COMPUTATIONS

GASOLINE-POWERED VEHICLE

LIFE CYCLE COST COMPUTATIONS

Item	Year 0	1	2	3	4	5	6	7	8
Fixed Invest.	0								
Vehicle Invest.	8166								
Fuel Cost		283	283	283	283	283	283	283	283
Discount Factor		.954	.867	.788	.717	.652	.592	.538	.489
Disc. Fuel Cost		270	245	223	203	185	168	152	138
		Total Discounted Fuel Cost = $1,584							
Maint. Cost		441	441	441	441	441	441	441	441
Disc. Maint. Cost		421	382	348	316	288	261	237	216
		Total Discounted Maintenance Cost = $2,469							
Salvage Cost									(817)
Discounted Salvage Cost									(400)
Disc. Yearly Cashflows	8166	691	627	571	473	429	389		(46)

Discounted Unit Life Cycle Cost = $11,819

Discounted Alternative Life Cycle Cost = $0 + 11,819x_1$

ELECTRIC-POWERED VEHICLE

LIFE CYCLE COST COMPUTATIONS

	Year									
Item	0	1	2	3	4	5	6	7	8	9	10
Fixed Invest.	0										
Vehicle Invest.	12249										
Fuel Cost		448	448	448	448	448	448	448	448	448	448
Discount Factor		.954	.867	.788	.717	.652	.592	.538	.489	.445	.405
Discounted Fuel Cost		427	388	353	321	292	265	241	219	199	181
	Total Discounted Fuel Cost = $2,886										
Maint. Cost		287	287	287	287	287	287	287	287	287	287
Discounted Maint. Cost		274	249	226	206	187	170	154	140	128	116
	Total Discounted Maintenance Cost = $1,850										
Battery Repl. Cost				2996		2996		2996		2996	
Discounted Battery Cost				2361		1953		1612		1333	
	Total Discounted Battery Cost = $7,259										
Salvage Cost											(735)
Discounted Salvage Cost											(298)
Disc. Yearly Cashfl.	12249	701	637	2940	527	2432	435	2007	359	1660	(1)

Discounted 10 Year Life Cycle Cost = $23,946

Discounted 8 Year Life Cycle Cost = (23,946/10) x 8 = $19,157

8 Year Life Cycle Vehicle Cost = (12249/10) x 8 = $9,799

8 Year Life cycle Fuel Cost = (2886/10) x 8 = $2,309

ELECTRIC-POWERED VEHICLE
LIFE CYCLE COST COMPUTATIONS (CONTINUED)

8 Year Life Cycle Maint. Cost (incl. Batteries)
= ((1850 + 7259/10) x 8 = $7,287

Discounted Alternative Life Cycle Cost = 0 + $19,157x_2$

COMPRESSED NATURAL GAS-POWERED VEHICLE

LIFE CYCLE COST COMPUTATIONS

	Year							
Item	0	1	2	3	4	5	6	7	8
Fixed Invest.	49570								
Vehicle Invest.	9794								
Fuel Cost		252	252	252	252	252	252	252	252
Discount Factor		.954	.867	.788	.717	.652	.592	.538	.489
Discounted Fuel Cost		240	218	199	181	164	149	136	123
	Total Discounted Fuel Cost = $1,410								
Maintenance Cost		333	333	333	333	333	333	333	333
Discounted Maint. Cost		318	289	262	239	217	197	179	163
	Total Discounted Maintenance Cost = $1,864								
Salvage Cost									(817)
Discounted Salvage Cost									(400)
Discounted Unit Yearly Cashflows	9794	558	507	461	420	381	346	315	(114)

Discounted Unit Life Cycle Cost = $12,668

Discounted Alternative Life Cycle Cost = $49,570 + 12,668x_3$

Note: Difference in unit life cycle cost from text is due to rounding of numbers.

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